GEORGIA INSTITUTE OF TECHNOLOGY — OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

[x] ORIGINAL [ ] REVISION NO. ______

Project No. A-3112 — DATE 12/7/81

Project Director: E. F. Knott — ~~School~~/Lab RAIL/MAD

Sponsor: Boeing

Type Agreement: Purchase Order No. 04-133859-0750N

Award Period: From 11/1/81 To 4/30/82 (Performance) ______ (Reports)

Sponsor Amount: $44,432 — Contracted through: GTRI/GIT

Cost Sharing: None

Title: Compact Range Feasibility and Design Study

ADMINISTRATIVE DATA

OCA Contact William F. Brown x 4820

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2) Sponsor Admin/Contractual Matters:

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Defense Priority Rating: None

Security Classification: None

RESTRICTIONS

See Attached None Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval – Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with None proposed

COMMENTS:

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FORM OCA 4:781

GEORGIA INSTITUTE OF TECHNOLOGY | OFFICE OF CONTRACT ADMINISTRATION

SPONSORED PROJECT TERMINATION SHEET

Date 7/7/82

Project Title: Compact Range Feasibility and Design Study

Project No: A-3112

Project Director: E. F. Knott

Sponsor: Boeing

Effective Termination Date: 4/30/82

Clearance of Accounting Charges: 4/30/82

Grant/Contract Closeout Actions Remaining:

- [x] Final Invoice and Closing Documents
- [ ] Final Fiscal Report
- [ ] Final Report of Inventions
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other ______

Assigned to: RAIL/MAD ~~(School~~/Laboratory)

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FORM OCA 10:781

A-3112

INTERIM REPORT
PROJECT NO. A-3112

COMPACT RANGE FEASIBILITY AND DESIGN STUDY

By
E. F. Knott, H. P. Cotten, and E. A. Nelson

Prepared for
THE BOEING COMPANY
P. O. BOX 3707
SEATTLE, WASHINGTON 98124

Under
Purchase Order No. 04–133859–0750N

March 1982

GEORGIA INSTITUTE OF TECHNOLOGY
A Unit of the University System of Georgia
Engineering Experiment Station
Atlanta, Georgia 30332

1982

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GIT/EES Project A-3112

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MARCH 1982

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SECTION 1
INTRODUCTION

This Interim Technical Report is the first of two documents to be submitted to the Boeing Military Airplane Company under Purhcase Order No. 04-133859-0750N. The Purchase Order was in response to Georgia Tech's Unsolicited Proposal RI-MAD-1112-R1, submitted on 14 October 1981. The effort constitutes the second of a three-phase study of compact ranges. In the first phase, Georgia Tech was awarded a contract to conduct a literature search on compact ranges, and several pertinent references were identified. As set forth in the above mentioned proposal, the second phase is a Feasibility Study of compact ranges, and the third phase is a Design Study.

The Boeing Military Airplane Company has decided to invest internal funds in the development of a unique and impressive indoor RCS measurement capability. The first of Boeing's plans has already been implemented in what is called an RCS Analyzer Facility. It is an anechoic chamber about 130 feet long instrumented with three CW millimeter wave radars (35, 64, 90 GHz). The facility is intended for model measurements, which is to say, scale models are measured to simulate full scale performance. The target models are suspended by strings between a pair of turntables, one mounted in the ceiling, the other in the floor. The support lines can be reeled in or paid out by stepping motors, and Boeing eventually hopes to be able to simulate actual flight dynamics by computer control of the motors.

To minimize chamber contributions and model/chamber interaction, Boeing intends to replace the CW radars. Georgia Tech performed a preliminary design and analysis of a series of radars, but Boeing later opted to buy a design concept from Hughes. Realizing that the mm wave range could be used only for small targets (antenna-to-target range is only 102 feet), thereby restricting full scale simulations to frequencies at and below L-Band, Boeing funded Georgia Tech to study the feasibility of designing and installing a phase correcting lens between the radar and target. That study is nearly complete [1].

In the meantime, Boeing is considering installing another indoor facility adjacent to the existing mm wave chamber. The purpose of the new chamber would be to provide an environment for the measurement of full scale targets up to 20 feet long at nominal frequencies from 2 to 18 GHz, with 1 to 40 GHz being desired goals. By necessity, the new facility must be a compact range because the internal volume will be only (about) 20 feet tall, 40 feet wide and 100 feet long.

Georgia Tech was issued verbal instructions to examine three approaches to a compact range concept. These were the use of a parabolodial reflector, a lens, and a phased array antenna. The purpose of any of the three approaches is to provide a uniform incident field over a target test region in far less space than is ordinarily available for far field radar echo measurements. The beam collimating properties of the reflector and the lens are well known, and a phased array antenna launches a collimated beam when properly excited. The objective of the current phase of the study was to select the most promising of the three approaches to obtaining a collimated beam. Georgia Tech finds that the reflector concept should be given the highest overall ranking when state-of-the-art technology and costs are considered.

The capability goals for the Boeing compact range are:

Frequency:	1 to 40 GHz (2 to 18 GHz nominal)
Pulse Width:	1 to 50 ns
Sensitivity:	-60 dBsm target
Working Volume	10 feet high, 20 feet square.

The string support system already in use in the RCS Analyzer Facility will be copied in the facility being planned, except that the turntables will be larger, perhaps 20 feet in diameter. The target test volume will be centered approximiately 2/3 of the chamber length from the "source" end of the chamber, and the "target" end of the chamber will be fitted with large doors to allow large targets to be brought into the chamber. The exact chamber dimensions have not been fixed, but for the purposes of this study, it has been assumed that the chamber will be at least 20 feet tall, at least 40 feet wide, but no more than 100 feet long.

With these constraints in mind, Sections 2 through 4 summarize the features we considered in deciding which of the three approaches is most attractive in satisfying the objectives of the compact range. Section 5 is a brief summary of the results; we find that the reflector concept has the highest potential for success.

SECTION 2
REFLECTORS

The first of the three concepts studied was the use of a metallic offset-fed paraboloidal reflector. The term "offset" stems from the fact that only a portion of a parabolic surface of revolution is used, that portion being chosen to minimize or avoid blockage of the reflected field by the feed. As a rule of thumb, the reflector must be at least twice the size of the intended target cross section region in the chamber to minimize the field taper from one side of the test region to the other. If targets as large as 10 feet by 20 feet are to be measured, this rule would suggest that the reflector must be 20 feet high and 40 feet wide.

If the offset paraboloid is obtained from the full paraboloid as shown in Figure 1a, the diameter of the full paraboloid is of the order of 50 feet. If it is obtained from the full paraboloid as shown in Figure 1b, the diameter of the full paraboloid exceeds 80 feet. These two cases correspond to having the feed placed in the floor (or ceiling) of the chamber or at a side wall. Generally, the performance of the reflector is better for higher F/D ratios, where F is the focal distance and D is the diameter of the full paraboloid; hence, the configuration shown in Figure 1a is the desired one.

This means that the feed should be placed at or above the ceiling, or on or below the chamber floor. The floor is probably the better location since the feed would be more accessible there than in the ceiling, even if it might have to be placed in a trench. Boeing's preliminary concepts include a pair of 20-foot diameter turntables, one mounted in the ceiling and the other in the floor, for suspending and rotating the test targets. The feed, therefore, must be at least 10 feet closer to the reflector

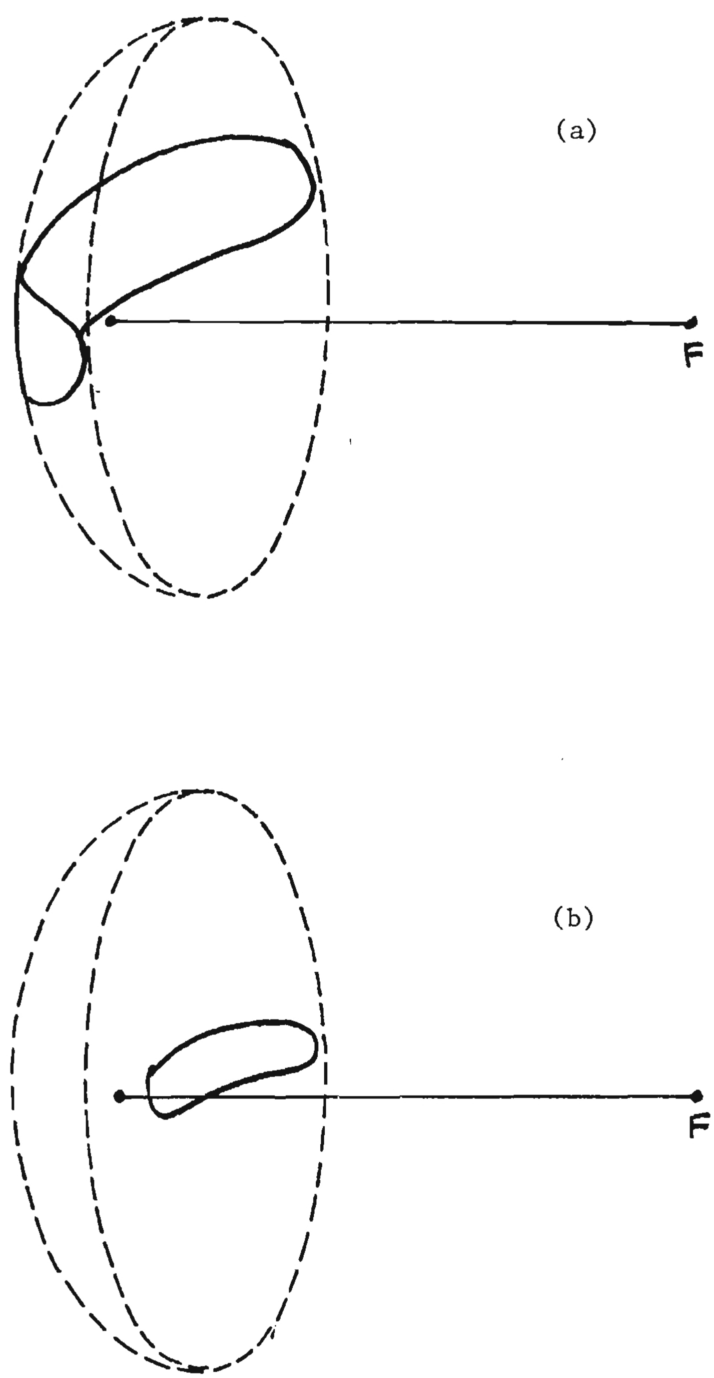

Figure 1. Two methods of obtaining an offest paraboloid

than the target axis of rotation, which we have assumed will be about 65 feet from the reflector. Allowing an additional 5 feet for clearance and a feed support fixture, this implies a focal length of about 50 feet. Thus, the F/D ratio for the reflector will be about 1:1.

A rule of thumb for a working tolerance for any reflector is $\lambda/32$. If this rule is applied to the highest frequency (generating the tightest tolerance) of expected operation, we obtain a working tolerance of 0.020 inch at 18 GHz and 0.009 inch at 40 GHz. Producing an antenna of this size to a tolerance of only 0.009 inch would be extremely difficult and very expensive. Obviously, we must strike a compromise and back away from such tight tolerances.

Richards [2] discusses profile accuracies in terms of an RMS (root-mean-square) profile error, ε, and lists the value achieved for six recent installations, as shown in Table 1. For the compact range, the equivalent round paraboloidal dish would be about 50 feet in diameter, and an interpolation of the data in Table 1 for this size yields a normalized profile error of ε/D =

TABLE 1. RMS ERRORS FOR SOME LARGE REFLECTORS

LOCATION	DIAMETER (feet)	RMS error (inches)	$\varepsilon/D (x\ 10^{-6})$
University of Texas	16	0.003	16
Aerospace Corporation	15	0.003	17
U.S.S.R. (Lebedev Inst)	72	0.020	23
Goonhilly (modified)	85	0.030	32
MIT - Haystack	120	0.050	35
CSIRO - Parkes	210	0.140	56

20×10^{-6}, implying an RMS error of 0.012 inch, somewhat less restrictive (and therefore less costly) than the 0.009 inch tolerance mentioned above. Nevertheless, an error of 0.012 inch corresponds to $\lambda/32$ at a frequency of 30.7 GHz, significantly higher than the 18 GHz upper limit for the compact range stated in Section 1.

Richards displays a chart (Reference 1, Figure 7.2) showing the efficiency of reflector antennas as a function of the RMS profile error in wavelengths. From that chart, the following values can be extracted for $\varepsilon = 0.012$ inch:

Frequency, GHz	Efficiency, percent
1	100
2	99
18	94
40	77

Thus an RMS profile error of 0.012 inch seems achievable and the reflector performance would not be seriously degraded at the higher frequencies.

Because of the large size of the reflector, it obviously cannot be made in a single piece; it must be fabricated of smaller subassemblies that can be transported from the fabrication facility to the site where it can be assembled. This construction technique will also minimize the risk of damage and possible surface deformation due to handling and transportation. The reflector will probably have to be built in sections using special assembly fixtures that control the surface dimensions. If the sections of the reflector are packed, handled, and transported with care, it should be possible to maintain the accuracy of the surface profile of the final assembly, as well as that of the sections themselves.

There are two forms of reflector breakdown that can be used to implement the sectional installation on site. In the first, prefabricated sections are bolted together by means of close-tolerance holes and fasteners. In the second, the reflector surface is attached to a rigid support structure by means of adjustable brackets, and the final surface contour is fixed by an on-site survey-and-set procedure.

If the prefabricated section concept is used, each section is a complete unit consisting of a support structure with the reflecting surface attached thereto. Each section should be sufficiently rigid and self-supporting that adjacent sections are not relied upon for support. Sections should be attached to adjacent sections by means of positive connections, such as precision pins mating in precision holes, at no more than three points. The tolerance of the locations of the attachment points must be such that the overall surface requirement is automatically satisfied.

If the reflecting surface contour is to be finalized by site adjustment, a strong, rigid support structure must be assembled on-site to receive preformed surface panels. A certain amount of adjustment must be allowed in the mounting of the panels so as to facilitate the final surface adjustments. These assemblies require that the basic support structure be rigid without any reliance on the reflecting surface for strength. The surface panels themselves must be rugged enough to withstand normal handling without measurable deformation.

The adjustment mechanism must have sufficient latitude to allow surface panels to be moved to the proper orientation. The adjustment must be a positive one in which the panel movement is directly related to the motion of the adjustment device. Each panel should be mounted on the basic support framework at no more than three points.

Several methods can be used to check the final contour. Perhaps the simplest one is the use of a precision steel tape stretched between a rigid fixture installed at the focus and the surface itself. Due to the finite sag in the tape and limited methods of holding the tape, the accuracy of this technique is limited to about 1/16 inch. Other techniques utilize laser survey instruments, and there are several companies equipped to perform this service*. Another method is the use of templates placed against the surface profile, but the large size of the reflector and the offset location of the focal axis make this method extremely difficult to use within the confines of the chamber.

The fabrication technique used in building the reflector surface will govern how the reflector is installed. Prefabricated sections must be small enough to fit on a flat bed trailer or inside a closed trailer. The sections would have to be hoisted by crane to the roof of the building on which the compact range is to be constructed. If the outer wall of the chamber is not a load-bearing wall, the prefabricated sections could be moved within the chamber and assembled, and the wall could be completed as the final phase of the installation.

If the site-adjustable panel construction method is used, the support structure could be made in pieces small enough to be hoisted to the roof and assembled within the chamber. The panels and the support structure sections could be made small enough to pass through the normal openings in the chamber.

Alternatively, the entire structure could be assembled on the roof before the chamber is built, which has the advantage of making it easier to assemble and check the reflector. However, this would exposure the reflector to possible wind damage, as well as mishaps during the construction of the chamber surrounding it. In all, considering the total cost of the pro-

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* One is DBA Systems, Inc., Melbourne, FL, 305-725-3711. Georgia Tech neither endorses nor declaims such services, and merely lists this company as an example.

ject and the delicate nature of the reflector, it seems unwise to expose the reflector to these hazards.

Scientific-Atlanta markets a commercial reflector for compact antenna ranges, but this reflector is much too small for the Boeing facility. The reflector has serrated edges, reportedly for the purpose of reducing edge diffraction. This is due, in part, to the fact that the pattern of the feed horn used to illuminate the reflector must be broad enough to minimize the amplitude taper across the target (or antenna) test region; the broadness of the pattern provides strong illumination of the rim of the reflector, and serrations have been used to reduce edge diffraction. Although a straightforward application of the geometrical theory of edge diffraction suggests that the serrations have no effect, measurements have apparently shown that the serrations are effective, or else they would not have been designed into the reflector. Whatever the case, whether it be edge serrations or absorbing material to suppress the edge effect, this must be considered in the reflector design.

The costs of building, installing, and checking the reflector are difficult to estimate with any accuracy, but Table 2 represents an estimate based on Georgia Tech's experience with a large (but smaller than the 20 foot by 40 foot reflector discussed above) dish. In that case, the dish was assembled from 9 foot by 9 foot subassemblies at a cost of $130,000 per subassembly (in 1978 dollars). The cost estimate of Table 2 includes a 15% annual inflation factor.

TABLE 2. ESTIMATED COSTS FOR 20 X 40 FOOT REFLECTOR

	($ thousand)
Fabrication	1820
Engineering and design (mechanical)	104
Feed horn design and fabrication (5 systems)	30
Engineering (edge treatment)	30
Installation	37
Surface profile alignment	30
Chamber testing (4 weeks)	20
Miscellaneous (rigging, fasteners, etc.)	10
Crane Rental	5
Shipping	12
TOTAL ESTIMATED COST	$2098

SECTION 3
LENSES

In a related study of lenses [1], Georgia Tech recommended that the Boeing Company procure a solid dielectric lens to collimate the beam of a millimeter wave instrumentation radar. As a rule of thumb, the lens diameter should be 1.5 to 2 times the maximum size of the target and should be placed as close to the lens as possible. In practice, it may be possible to move the lens back as many as 3 or 4 lens diameters from the target, but this has not yet been verified. If the lens must be at least 150% bigger than the target, the lens may have to extend across the entire vertical chamber dimension.

The previous study showed that the reflections from a lens interposed between the target and the radar can exceed the main bang transmitter-to-receiver leakage by as much as 10 to 15 dB, therefore a receiver protection device may have to be used. It takes a finite time to switch such a device, and the shorter the time available, the more difficult the design. The lens return should precede the target return by at least a few dozen nanoseconds, the more the better, to allow a sufficient time for the receiver to recover its nominal sensitivity. Thus, the lens should be placed no closer than 20 or 30 feet from the target.

For the sake of example, assume that the lens can be no closer than 20 feet from the nearest extreme of a 20-foot long target. This will allow a 40-nanosecond receiver recovery time, probably as short a time as is possible without the sacrifice of receiver sensitivity or the complexity of sophisticated timing circuits. If the target is rotated about its midpoint for RCS measurements, then the lens can be no closer than 30 feet from the axis of rotation. We anticipate that the axis of rotation will be of the order of 2/3 of the length of the chamber from the transmitter, or about 65 feet away. This allows about 1/3 of the chamber length between the target and the rear wall, and is probably as close to the rear wall as the target should be placed. Thus, the lens will probably have to be as close as 30 to 35 feet from the transmitter.

We assume that a 30-foot diameter lens will be required for adequate illumination of a 20-foot wide target. The lens may be truncated at the top and the bottom because the chamber is not likely to be more than 20 or 25 feet tall. This truncation is not expected to affect the performance of the lens over a 10-foot vertical dimension centered on the chamber axis. However, the short focal distance (30 to 35 feet) will force the lens to be a thick one. In actual fact, the F/D ratio will be about unity.

The related lens study suggested that it may be very difficult to build a lens of this size using foamed plastic, and that a solid plastic material is preferable, even though the lens reflections will be 10 to 15 dB higher. In that study, Plexiglas® or Lucite® were recommended because they have low losses and essentially frequency-independent dielectric constants. These plastics weigh about 74.26 pounds per cubic foot.

That study also showed that the reflections from a plano-convex lens are smaller if the flat side of the lens faces the transmitter instead of the target. Although the lens profiles are slightly different for the two cases, we have explicit formulas for the lens thickness and volume in one case, but not the other. For large indexes of refraction, the differences are only a few percent, hence we will base our thickness and volume estimates on the case when the flat side of the lens faces the target.

The thickness of the lens is given by

$$T = \left\{\left[F^2 + \frac{1}{4}\ \frac{n+1}{n-1}\, D^2\right]^{1/2} - F\right\}/(n + 1) \qquad (1)$$

and the volume is given by

$$V = \pi (n - 1) T^2 \{F + \frac{1}{3} (n + 1) T\} \tag{2}$$

where T is the lens thickness, V is its volume, F is its focal length, D is its diameter and n is the refractive index of the lens material. At 10 GHz, the dielectric constant of the polymethacrylates is about 2.58, implying a refractive index of 1.606.

The thickness of a 30-foot diameter lens with a focal length of 30 feet will be about 5.07 feet; the volume of a complete (untruncated by floor and ceiling) lens will be about 1684 cubic feet. The untruncated lens would weigh abut 62.5 tons; if 25% of the lens is clipped off by the floor and ceiling, it would still weigh about 47 tons. This is clearly an extremely heavy and bulky device, to say nothing of the sheer cost of the material itself, which might exceed $100,000.

Let us therefore consider the case if the lens were only 20 feet in diameter and if the focal length could be increased to 40 feet. In this event, the lens would be less than half as thick (1.94 feet), its volume would be only 299 cubic feet, and it would weigh 11.1 tons. It is doubtful that the edges of a 20-foot target would be adequately illuminated, however, and the receiver recovery time would have to be very short due to the close spacing between the lens and the target.

No matter whether the lens is 20 feet or 30 feet in diameter, there are difficult technical problems to solve, and estimating the probable cost is equally difficult. For one, probably no one in the world has ever produced a solid piece of plastic this large, and it is doubtful if a piece this size has even been assembled from smaller pieces. There are essentially only two options available: to fabricate the lens from a collection of smaller pieces or to cast the lens in a single piece.

Fabrication will require the lamination of several slabs, none of which is likely to be more than an inch or two thick. No single slab is likely to be large enough to run from one side of the lens to the other, except in the vicinity of the lens apex, hence, the assembly will consist of laminations and butt joints. It may be possible to produce or acquire slabs with smooth surfaces, perhaps by mean of a rolling operation. The lamination process requires smooth surfaces and layers are bonded together by applying the base polymer to the faces, then holding the faces together under pressure until the bond sets. It is uncertain if this process will induce variations in the local refrative index at the interface between layers. If so, the lens performance may suffer.

The lamination of methacrylates is routine for small assemblies, but it may be extremely difficult for an assembly the size of a 20-foot or 30-foot lens. For one, the bonding agent must be spread uniformly and thinly over the mating surfaces, and it is not known if this can be done for surfaces as large as several hundred square feet. For another, the surfaces must be brought into contact in such a way as to "roll out" any air bubbles that tend to get trapped. Both operations would require the design, construction, and testing of large, special purpose fixtures, one for applying the bonding agent to the mating surfaces, and the other for handling large slabs of material and bringing their faces together properly.

Within a given layer (lamination) of the lens, there may be several butt joints, since it may take several smaller slabs positioned end-to-end and side-to-side to establish that layer. The slab edges, like their surfaces, must be smooth and flat, hence they will have to be machined before the lay-up. Even if large slab-handling and glue spreading fixtures are available, it may be difficult to properly align the butt joints due to seepage or roll-out of the bonding agent at the site of the joint.

An alternative to assembly of the lens from several smaller slabs is to cast the lens. This may well be as difficult as an assembly process. A large mold would have to be fabricated (not necessarily to the precise contour of the finished product) capable of containing as much as 9000 gallons (163 55-gallon drums) of material. The mold would have to be massive to support this weight, and a huge mixing/depositing fixture would have to be designed to instill the reacting liquids. The mold would have to be coated with a release agent, and it would have to be designed to be broken away from the casting.

The reacting polymer and catalyst give off heat, but the large quantity of material involved may cause heat to be trapped destructively in the interior of the thicker parts of the casting. The outer layers of casting would cool sooner than the inner volumes, and the differential cooling rate may lead to internal and external cracks and stresses unless the entire mold and its contents were built within a curing chamber.

Even if these problems could be solved, there remains the task of machining the lens surface to the required contour. Imposing a rule-of-thumb tolerance of 1/32 wavelength at the highest frequency of operation (18 GHz), we find a surface tolerance requirement of 0.020 inch; this is not unreasonable for a structure a few feet in size, but is certainly unreasonable for one 20 or 30 feet across.

Surface machining would require a 3-axis milling machine or the fabrication of a special fixture to be used with a large rotary table. Finally, even if this could be done, there is the task of handling, moving and installing such a massive monolith to its final position.

Although the sheer size and uncertain outcome of such a project virtually precludes further consideration, we have made a gross estimate of the possible costs involved. These are summarized in Tables 3 and 4, and the cost is likely to approach $1 million.

TABLE 3. ESTIMATED COST OF LAMINATED LENS
(thousands of dollars)

Material	150
Bond agent spreading fixture	100
Lay-up fixture	100
Assembly	100
Final Machining	250
Installation	50
TOTAL ESTIMATED COST	$750

TABLE 4. ESTIMATED COST OF CAST LENS
(thousands of dollars)

Materials	150
Mixing Fixture	100
Mold	100
Casting Operation/Curing/Mold removal	100
Final Machining	250
Installation	50
TOTAL ESTIMATED COST	$750

SECTION 4
ARRAYS

The third concept considered was the installation of a plane array antenna at one end of the proposed chamber. The array consists of a collection of small antenna elements, typically less than a wavelength in size and uniformly distributed across the transverse chamber dimension. The array elements must be excited in phase to launch a plane wave down the chamber axis, hence a power distribution network must be included in the array design. This network would occupy some volume behind the array, but probably no more than the volume devoted to a parabolic reflector concept. Significantly, a single array would not cover the entire frequency range from 2 to 18 GHz (nor 1 to 40 GHz). Consequently, some provision would have to be made for moving one array out of the chamber and swinging another into place. A system of three arrays could cost more than $10 million.

4.1 CONVENTIONAL ARRAYS

At first glance, a uniformly excited array might appear to be a good candidate for plane wave illumination of a test target because uniform fields can be provided over a transverse plane nearly as large as the array itself. Unfortunately, a single array cannot cover the entire frequency range because of the limited bandwidth of the array elements. For example, the bandwidth of large arrays used in beam scanning systems is seldom more than about 10%. The array under consideration need not be scanned, of course, but it may be difficult to design broadband array elements.

Such elements tend to be several wavelengths in size, whereas conventional array elements must be typically less than a wavelength in size to prevent lobes from radiating or adversely affecting the element impedance. Incipient grating lobes can cause the element impedance to vary erratically with changing frequency and should therefore be avoided. If the grating lobes are permitted to radiate, the power illuminating the chamber walls may be up to six times greater than that in the desired main beam. In addition to the loss in illumination efficiency, the residual chamber reflectivity may be increased.

If we assume that a 200% element bandwidth is achievable, then it will require no fewer than 3 arrays to cover the frequency range from 2 to 18 GHz. This means that two of the arrays would have to be stowed away while the third was in operation; although the handling of these large structures is physically possible, it is certainly an unattractive proposal to consider doing so. Since there would be no place within the chamber to store the extra arrays, the transmitting end of the chamber would have to be fitted with large doors so that the arrays could be moved in and out. The chamber might even be designed with "transmitter walls," each array being mounted in a movable wall that "plugs onto" the end of the chamber.

The cross section of the chamber will probably be greater than 40 feet wide by 20 feet high, covering an area of 800 square feet. It may not be necessary to completely fill the rectangular cross section with radiating elements, and the area can be reduced to about 628 square feet if only the inscribed ellipse is utilized. If this area is filled with array elements arranged in a triangular matrix, the elemental area is $2/\sqrt{3}$ times the square of the element spacing. Thus, we can estimate the number of elements required if we know the element spacing.

If the cost of the array depends linearly on the number of elements, then the high band array will be the most costly by far. The elements must be less than a wavelength apart, say 0.9λ, at the highest frequency of operation to prevent grating lobes. At 18 GHz, it will require about 225,000 elements to build the array. At the highest frequency of the low band system (say 4 GHz) it would require only 50,000 elements. (All three arrays could be built with a total of about 300,000 elements.) Since the array elements need to be broadband, it would not seem pessimistic to estimate the element cost at $10 each.

Control of the amplitude and phase of element excitation over the required bandwidth will almost certainly require a constrained feed. This will probably be implimented using broadband stripline power splitters, and the cost will probably be in the neighborhood of $10 per element.

The radiating elements may be connected to the feed system individually or in small groups (panels). In the ideal case, the radiators would be fabricated integrally with the feed system, but this can be done only for narrow frequency bands. Thus we are led to the possible requirement for developing connectors. If the connector has two mating parts, it might cost $5 for each part, for a total connector cost of $10.

These estimates are for a single polarization, but routine RCS measurements usually demand multiple polarization capability. Providing the full matrix --- transmit and receive horizontal and vertical, for example --- would be very costly to implement because of the difficulty of maintaining isolation between the two orthogonal polarization channels. Thus we assume it sufficient to transmit and receive horizontal or vertical polarizations alone, and not the cross polarizations.

The use of dual polarized elements would more than double these costs, and it might even triple them. This is because two complete feeds and two complete sets of connectors would be required, in addition to the elements themselves. An alternative to the double feed system is a switch for each element, but this is likely to be even more costly.

Other methods of obtaining dual polarization can be conceived. One idea is to make the array aperture a 2:1 rectangle instead of an ellipse and to split it into two squares. Each square could be rolled 90 degrees, but if this is to take place without removing the array from the chamber, the diagonal dimension of each square would have to be less than 20 feet, thereby reducing the array area to 566 feet. It is conceivable that special fixtures could be designed to manipulate the arrays in such a way that the full 800 square feet could be utilized, but this would drive up the cost of the system.

Another approach to the dual polarization problem is the use of polarization grids provided the necessary bandwidth could be achieved. Meander line polarization grids for converting linear to circular polarization have been designed to operate over octave bandwidths. Such bandwidths may be somewhat more difficult to achieve for grids designed to produce a 90-degree polarization twist. Each polarization grid would actually be two or more grids of meander lines lying in parallel planes. The spacing between the parallel grids to obtain the 90-degree polarization twist must be greater than that needed for circular polarization. However, a 90-degree polarization twist grid can probably be designed and would cost about $300,000 per system (or $900,000 for three octave bandwidth systems). The grids would have to be moved in and out of the chamber to switch the polarization. The total estimated cost for three arrays is summarized in Table 5.

TABLE 5. ESTIMATED COST FOR THREE ARRAYS

	(Millions)
300,000 element radiators at $10 each	3.0
Feeds for three array systems	3.0
600,000 connectors at $5 each	3.0
3 polarization grids at $300,000 each	0.9
Mechanical/physical structure, assembly miscellaneous	1.1
TOTAL ESTIMATED COST	$11.0

4.2 ALTERNATIVE CONCEPTS

In theory, it is possible to use radiating elements of any size in a non-scanning array, so long as each element is uniformly excited. The goal, whether the elements are large or small, is to achieve a uniform distribution of energy over the entire aperture. If this can be done with fewer elements, the net cost could be reduced even if the per-element cost would be much greater. The limitations of the large-element concept would have to be evaluated, possibly using a computer program like the one developed to study lenses. One would have to simulate the field distributions that might exist with actual elements and the program would compute the near zone fields.

A conceivable configuration might be an array of large horns, each of which would be fitted with a lens designed to correct the phase deviation at the aperture. If the aperture of each horn were 10 square feet, it would require 80 horns to fill the chamber cross section. At a cost of, say, $10,000 per horn, it would cost $0.8 million to cover the chamber cross section. Unfortunately, it would require more than one such system to cover the entire frequency band, and the need to be able to exchange arrays (move them in and out of the chamber) would still be present.

Another way of reducing the number of array elements is to use only part of the aperture at any given time. The most extreme form of this concept is the movement of a single element through all the element positions, with the received signal being recorded at each position. This would allow the reconstruction of the entire aperture performance digitally at a later time. Naturally, the data handling and time required for such a extreme case would be tremendous, but a tradeoff between partial aperture size, time, and data handling requirements might be made. Mechanical scanning techniques, tolerances in array positioning, and other practical problems would have to be addressed.

SECTION 5
CONCLUSIONS

The above study of the three approaches suggests that the lens concept may be the least costly, although it must be admitted that there is very little prior information upon which to base those cost estimates. However, due to the sheer mass and bulk of the lens, there is no established technology and the risk is very high. The phased array concept appears to be extremely costly and it is by no means clear that broadband elements could be developed for use in the array. The reflector concept, on the other hand, requires no more than existing state-of-the-art technology and its cost --- though high --- is less than that of the phased array concept. In an attempt to assign ratings based on cost and feasibility, we summarize the results in Table 6 below.

Georgia Tech therefore recommends that Boeing give the reflector concept the highest priority in building its new compact range.

TABLE 6. RELATIVE RATING AND COST

Concept	Risk	Cost ($ millions)
Reflector	low	2.1
Lens	high	0.8
Array	medium	11.0

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1. E.F. Knott, "Lens Feasibility and Design Study," Interim Report on Project No. A-3003 under Purchase Order No. 64-132568-0750N, Georgia Institute of Technology, Engineering Experiment Station, December 1981.

2. C.J. Richards (editor), Mechanical Engineering in Radar and Communications, Van Nostrand, Reinhold Co., London, 1969.

A-3112

Final Technical Report

GIT/EES Project A-3112

COMPACT RANGE FEASIBILITY AND DESIGN STUDY

By

E. F. Knott

Prepared for

THE BOEING COMPANY
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Under

Purchase Order No. 04-133859-0750N

Prepared by

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June 1982

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SECTION 1
INTRODUCTION

This Final Technical Report is the second of two documents submitted to the Boeing Military Airplane Company under Purchase Order No. 04-133859-0750N. The first document was an Interim Technical Report [1] that summarized Georgia Tech's rating of three possible compact range design concepts: reflectors, lenses, and phased array antennas. In that report, Georgia Tech recommended that the reflector concept be used because of the large body of reflector technology that exists.

The purpose of any of the three approaches is to provide a uniform incident field over a target test region that occupies substantially less space than is ordinarily available for far-field radar echo measurements. The beam collimating properties of the reflector and the lens are well known, and a phased array antenna launches a collimated beam when properly excited.

The capability goals for the Boeing compact range were given as

Frequency:	1 to 40 GHz (2 to 18 GHz nominal)
Pulse Width:	1 to 50 ns
Sensitivity:	-60 dBsm target
Working Volume:	10 feet high, 20 feet square.

The string support system already in use in Boeing's RCS Analyzer Facility was to be copied in the facility being planned, except that the turntables would be larger, perhaps 20 feet in diameter. The target test volume was to be centered approximately 2/3 of the chamber length from the "source" end of the chamber, and the "target" end of the chamber will be fitted with large doors to allow large targets to be brought into the chamber. The exact chamber dimensions have not been fixed; the study was based on assumptions that the chamber would be at least 20 feet tall, at least 40 feet wide, but no more than 100 feet long.

However, Georgia Tech was informed on 16 April 1982 that the maximum target size would be approximately 8 to 10 feet, not 20 feet. The smaller target size would allow the use of a smaller reflector or lens, thereby reducing costs. In this report, we consider the impact of smaller targets on the cost of the reflector and lens concepts, as described in Sections 2 and 3. Georgia Tech's conclusions and recommendations are presented in Section 4. If one is prepared to accept some degradation in the data collected in a compact range, the most economical approach is to purchase a commmercial reflector.

SECTION 2
REFLECTORS

Figure 1 illustrates the approximate volume available for the compact range facility. It is adjacent to the existing millimeter wave measurement chamber on the roof of a building and runs along the length of the existing structure. The main area available is about 110 feet long, but it can be lengthened by extending either the far end to the edge of the roof or the near end past the control room of the existing facility. The width is limited to the 40 or 45 feet available between the existing structure and another edge of the roof.

A rule of thumb for compact range reflectors is that the reflector should be at least twice the maximum target size. Since targets are expected to be no more than 8 to 10 feet in size, the reflector can be sized at 20 feet (these sizes are half those assumed in Georgia Tech's prior studies on this contract). The targets are expected to be thinner than they are long or wide, hence the vertical reflector dimension may be safely set at 15 feet or so.

The target should be within two reflector diameters from the reflector itself; if we use the 15-foot vertical dimension as the reflector diameter, this places the target about 30 feet away. For adequate separation of the target return from the rear wall return, the rear wall should be at least 30 feet behind the target. The full 40-foot width of the available space will minimize interactions between returns from the target and the side walls. Therefore, the floor plan of the chamber should be about 40 feet wide and 60 feet long.

A possible layout for the compact range is shown in Figure 2. It will fit comfortably beside the existing millimeter wave facility, even with a 30 by 40 foot extension behind the rear wall to provide a model preparation area. It is assumed that the test targets will be string-suspended between a pair of 10-foot turntables mounted in the floor and ceiling, as in the existing facility. These rotators will have to be moved in and out of the chamber as suggested in the diagram, hence there must be an absorber-covered

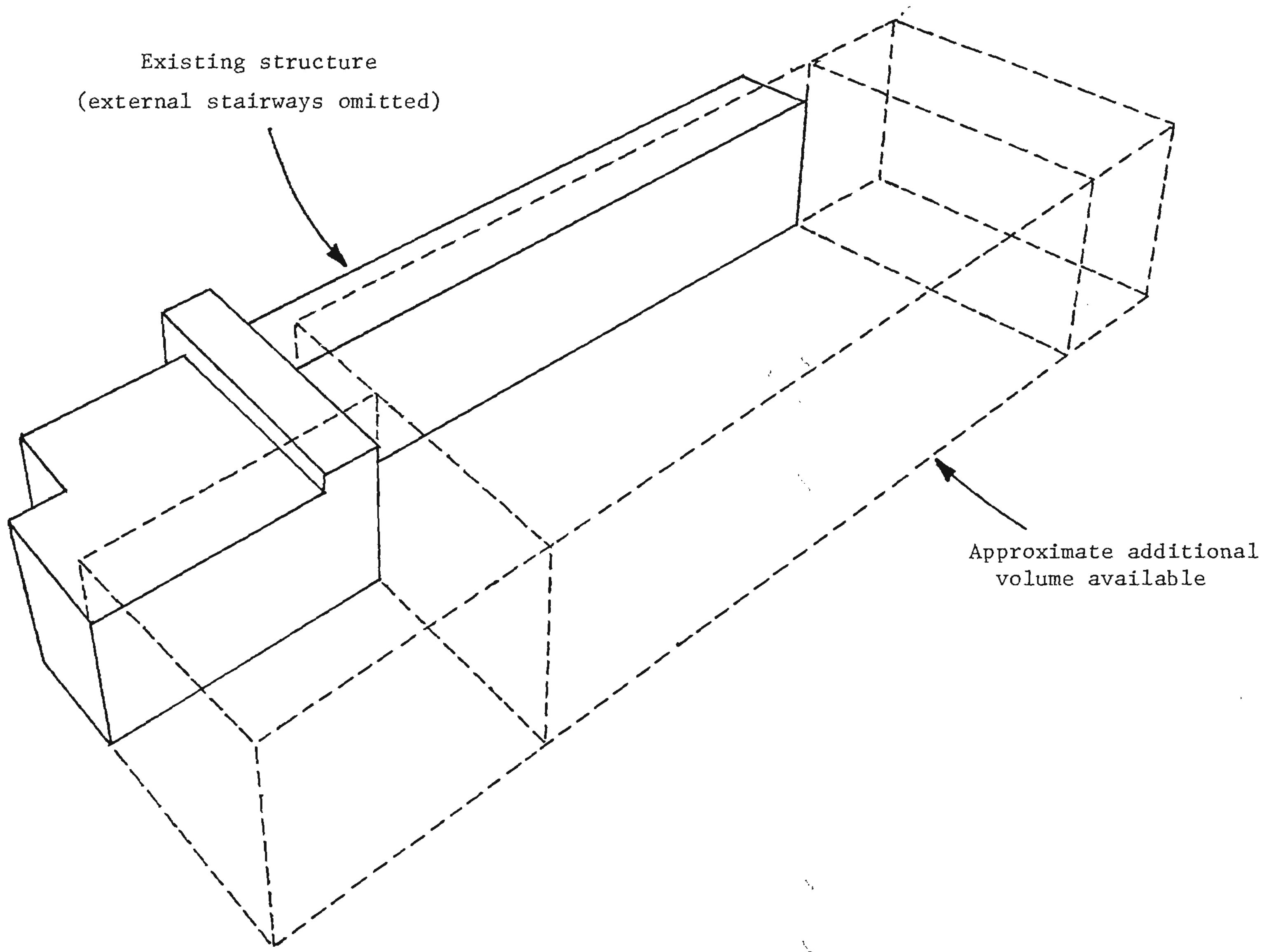


Figure 1. Approximate volume available for compact range facility.

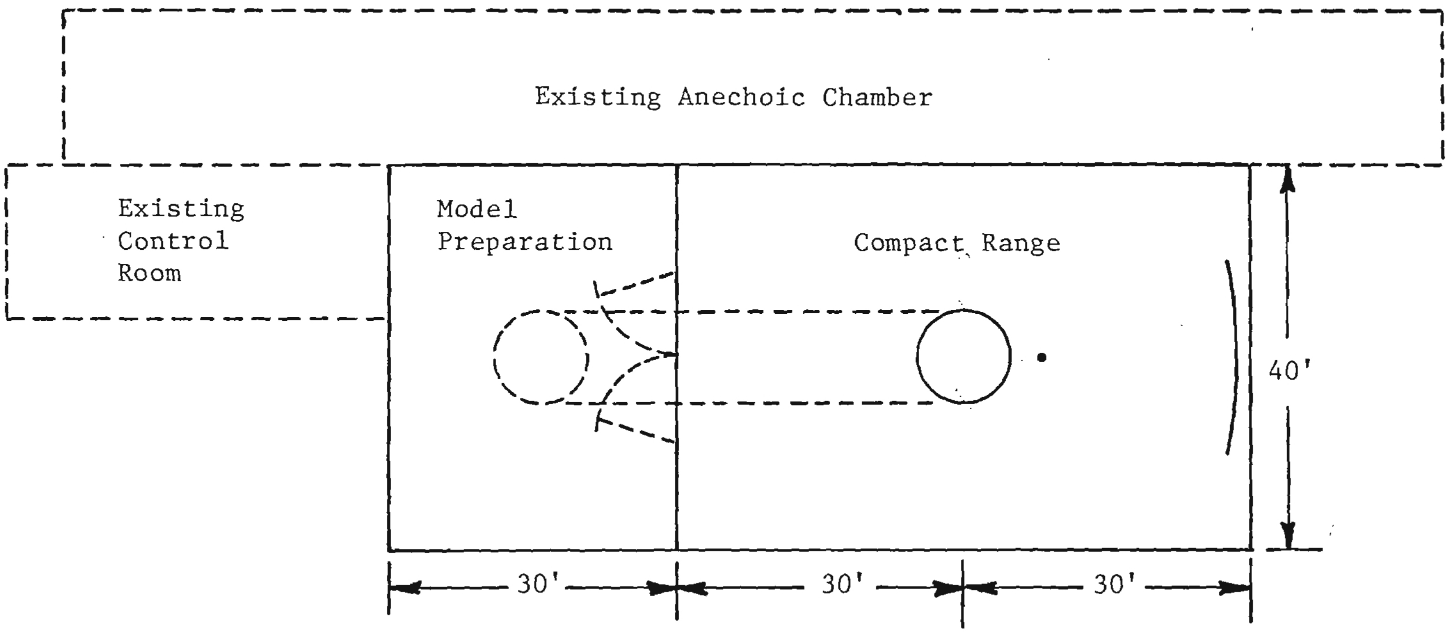


Figure 2. Compact range layout. Target rotators move in and out of the compact range as they do in the existing facility.

set of doors in the rear wall. The feed for the reflector must be forward of the target rotators, hence the focal distance must be of the order of 20 feet.

For reasons given in Georgia Tech's interim report, the feed should be placed near the floor or ceiling of the chamber, as opposed to the side walls. If placed near the ceiling, the feed would be inconvenient for adjustment or installation; if placed near the floor, it might require a false floor under the chamber. The subfloor structure required for the target rotator translation belt or track may have room enough for the feed and the waveguide runs to the transmitting and receiving equipment.

As pointed out by Howell [2], the ideal electric field radiation pattern of the feed should vary as $\sec^2(\theta/2)$, where θ is the angle subtended by the paraboloidal axis and a ray emitted by the feed. This feed pattern variation helps maintain a uniform field intensity over the reflector aperture, thereby giving a uniform field over the test target region. Figure 3 illustrates the $\sec^2(\theta/2)$ radiation pattern: Howell achieved an approximation of this pattern with a dipole backed by a conical ground plane.

The edges of a reflector 20 feet wide with a focal length of 20 feet subtend an angle $\theta = 26.6$ degrees, hence only a small part of this pattern would be used. The intensity of illumination at the reflector edges is barely 0.5 dB greater than at its center. On the other hand, this edge illumination is much stronger than would be desired if one were concerned with edge-diffracted rays reaching the target.

Interference due to edge diffraction can be significant. One way to examine the effect is to use Keller's geometrical theory of diffraction (GTD) [3]. Basically, Keller introduced the notion that an incident ray spawns a cone of diffracted rays, as shown in Figure 4, with the cone half angle equal to the local angle subtended by the edge and the incident ray. The theory is quasi-specular, in that diffracted rays are constrained to lie along generators of the forward cone and nowhere else. In the limit when the incident ray is perpendicular to the edge, the diffraction cone fans out to a disk.

Consider now the rim of a paraboloid of revolution. A ray emanating from a feed placed at the focus strikes the edge (not the surface) at right

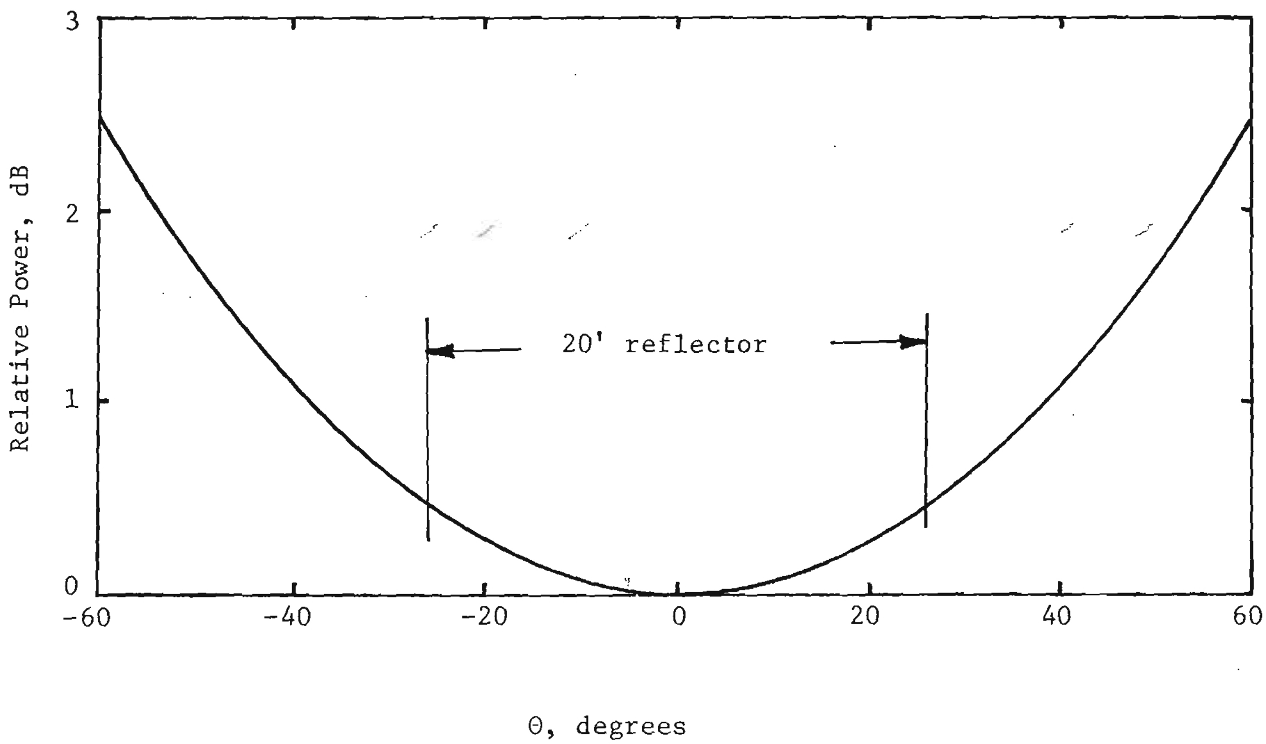


Figure 3. Sec^2 $(\Theta/2)$ radiation pattern.

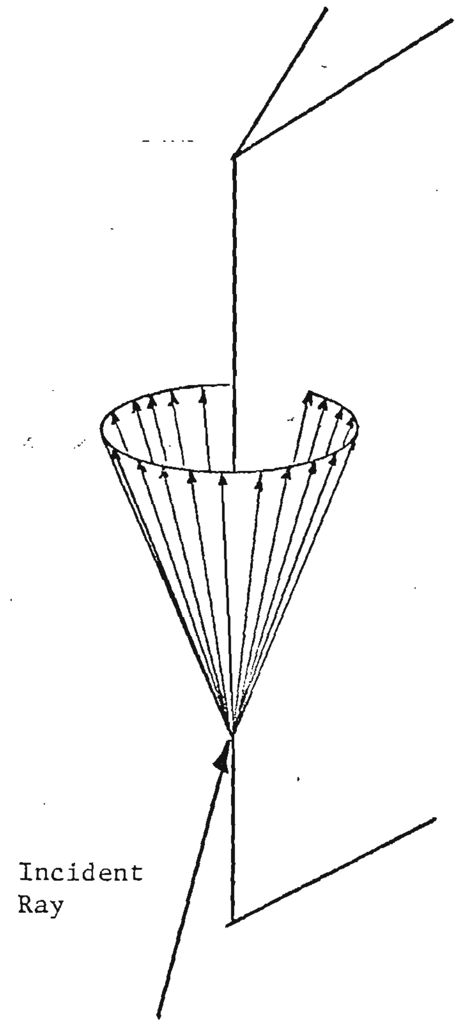


Figure 4. Keller's theory introduced the concept of a cone of diffracted rays spawned by a single incident ray hitting an edge.

angles. Therefore, the diffracted rays from a point on the edge lie in the plane containing the point and the axis of the paraboloid. There is an infinity of points around the rim where this occurs, consequently there is an infinity of planes passing through the target region, all of them intersecting at the paraboloid axis, and no point in the target region is invulnerable to edge-diffracted rays.

According to Kouyoumjian [4], the strength of a diffracted ray depends on the incident polarization. For an incident electrical polarization E_i parallel to the edge, the diffracted field is

$$E_d = E_i \frac{e^{iks} e^{i!/4}}{(2!ks)^{1/2} \sin b_o} (X - Y) A \tag{1}$$

and for an incident magnetic polarization H_i parallel to the edge,

$$H_d = H_i \frac{e^{iks} e^{i!/4}}{(2!ks)^{1/2} \sin b_o} (X + Y) A \tag{2}$$

In these expressions, s is the distance from the edge point to the far field point where the diffracted field is to be evaluated, $k = 2!/g$ is the free space wave number, b_o is the angle subtended by the incident ray and the edge, A is a factor that depends on the type of incident wave exciting the edge, and X and Y are diffraction coefficients that relate the amplitude of the diffracted ray to the directions of incidence and diffraction.

For plane, cylindrical, and conical incident waves, the factor A is unity. For spherical waves,

$$A = [s'/(s + s')]^{1/2} \tag{3}$$

where s' is the distance from the source to the edge point. The diffraction coefficients are

$$X = \frac{(1/n)\ \sin(\pi/n)}{\cos(\pi/n) - \cos[(\phi - \phi_o)/n]} \tag{4}$$

$$Y = \frac{(1/n)\ \sin(\pi/n)}{\cos(\pi/n) - \cos[(\phi + \phi_o)/n]} \tag{5}$$

where ϕ_o and ϕ are the angles of incidence and diffraction as shown in Figure 5. The edge has been represented as a wedge with an interior wedge angle α, and n is the exterior wedge angle normalized with respect to π radians. The X diffraction coefficient becomes singular at the shadow boundary, but Y becomes singular at the reflection boundary. Thus, GTD fails in those directions.

One can assess the amplitude of the interference due to edge diffraction, yet avoid the complexity of dealing with a three-dimension problem, by establishing the two-dimensional problem illustrated in Figure 6. This is a parabolic cylindrical reflector illuminated by a line source at the focus F. We assume the source has the $\sec^2(\theta/2)$ azimuthal pattern mentioned above, hence the wave reflected by the parabolic cylinder is uniform in phase and amplitude across the reflector aperture. The collimated beam will propagate toward the target region some distance L from the plane of the reflector edges.

In addition to the planar wave reflected by the cylinder, diffracted waves due to the reflector edges will also propagate to the target region. We choose a point P located some distance x from the plane of symmetry to evaluate the total field strength. The distances R_1 and R_2 between the edges and P are

$$R_1 = [L^2 + (D/2 - x)^2]^{1/2} \tag{6}$$

$$R_2 = [L^2 + (D/2 + x)^2]^{1/2} \tag{7}$$

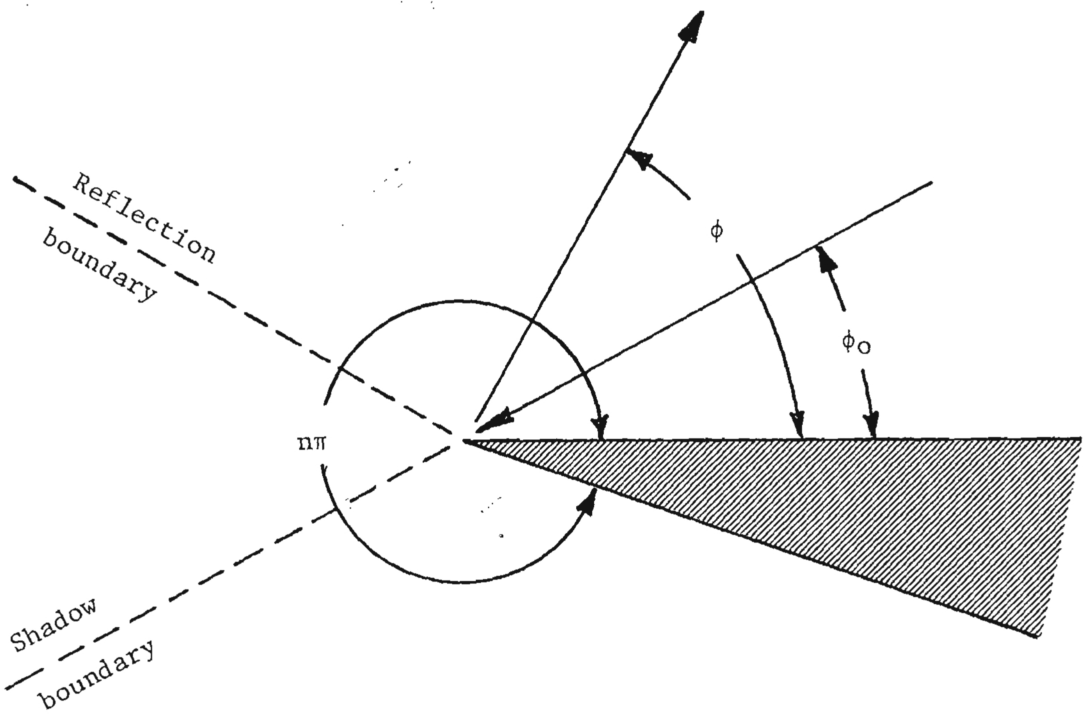


Figure 5. Wedge geometry.

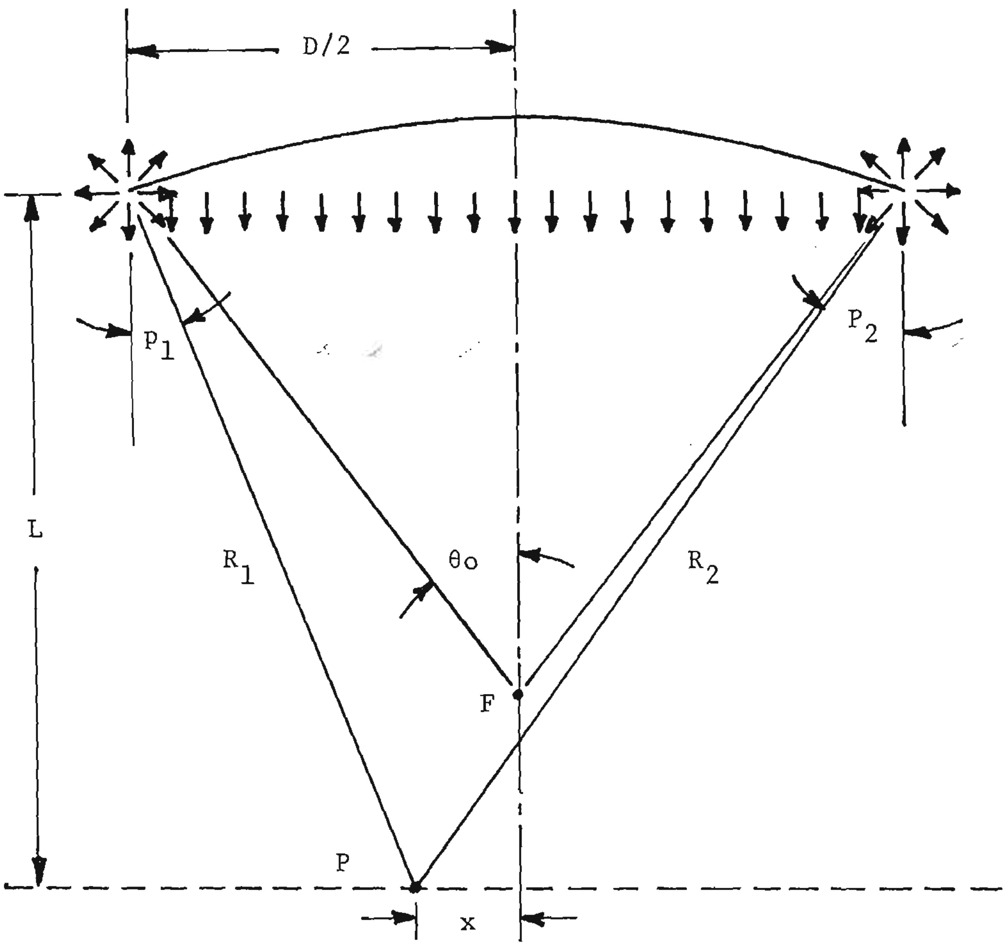


Figure 6. Parabolic cylindrical reflector for assesing edge diffraction effects.

Since this is a two-dimensional problem, $\beta_o = \pi/2$.

The reflector surface will be assumed to be a metallic sheet curled into the required parabolic shape. The edges of the sheet have no interior angle, hence n = 2 for the diffraction coefficients X and Y. The ray arriving at each edge from the focus makes an angle of $(\pi - \theta_o)/2$ with the tangent plane at each edge, hence

$$\phi_o = (\pi - \theta_o)/2 \tag{8}$$

From the geometry of Figure 6, it will be found that the diffracted angles ϕ_1, and ϕ_2 are

$$\phi_1 = (\pi + \theta_o)/2 - p_1 \tag{9}$$

$$\phi_2 = (\pi + \theta_o)/2 - p_2 \tag{10}$$

where

$$p_1 = \text{arc tan}\,\frac{D - 2x}{2L} \tag{11}$$

$$p_2 = \text{arc tan}\,\frac{D + 2x}{2L} \tag{12}$$

Inserting these value in Equations (4) and (5), the diffraction coefficients for the two edges are

$$X_1 = -\tfrac{1}{2}\sec[(\theta_o - p_1)/2] \tag{13}$$

$$Y_1 = -\tfrac{1}{2}\csc(p_1/2) \tag{14}$$

$$X_2 = -\tfrac{1}{2}\sec[(\theta_o - p_2)/2] \tag{15}$$

$$Y_2 = -\tfrac{1}{2}\csc(p_2/2) \tag{16}$$

Assuming unit incident field strength, the total field at P is

$$E, H = 1 + \frac{e^{i\pi/4}}{(2\pi)^{1/2}} \left(\frac{e^{ikR_1}}{(kR_1)^{1/2}} (X_1 \mp Y_1) + \frac{e^{ikR_2}}{(kR_2)^{1/2}} (X_2 \mp Y_2) \right) \tag{17}$$

The total field as given by Equation (17) at a freqency of 10 GHz is plotted in Figure 7 for a parabolic cylindrical reflector 20 feet wide with a focal length of 20 feet. The probe trajectory lies at a distance L = 28 feet from the apex of the reflector. Near the reflector axis, the net perturbation is about +0.5 dB, but rises to a value of about +0.7 dB 5 feet from the axis. The periodictiy of the perturbations is related to the angles p_1 and p_2, but the derivation will not be given here. The perturbations are greater for H-polarization than for E-polarization because both diffraction coefficients in Equation (17) have the same sign and they are added for H-polarization, but subtracted for E-polarizations.

Along the reflector axis, p_1 and p_2 are about 19.7 degrees, and θ_o is about 28.1 degrees. From these values, the diffraction coefficients are

$$X_1 = X_2 = -0.501 \tag{18}$$

$$Y_1 = Y_2 = -2.93 \tag{19}$$

For E-polarization,

$$X_1 - Y_1 = X_2 - Y_2 = 2.43 \tag{20}$$

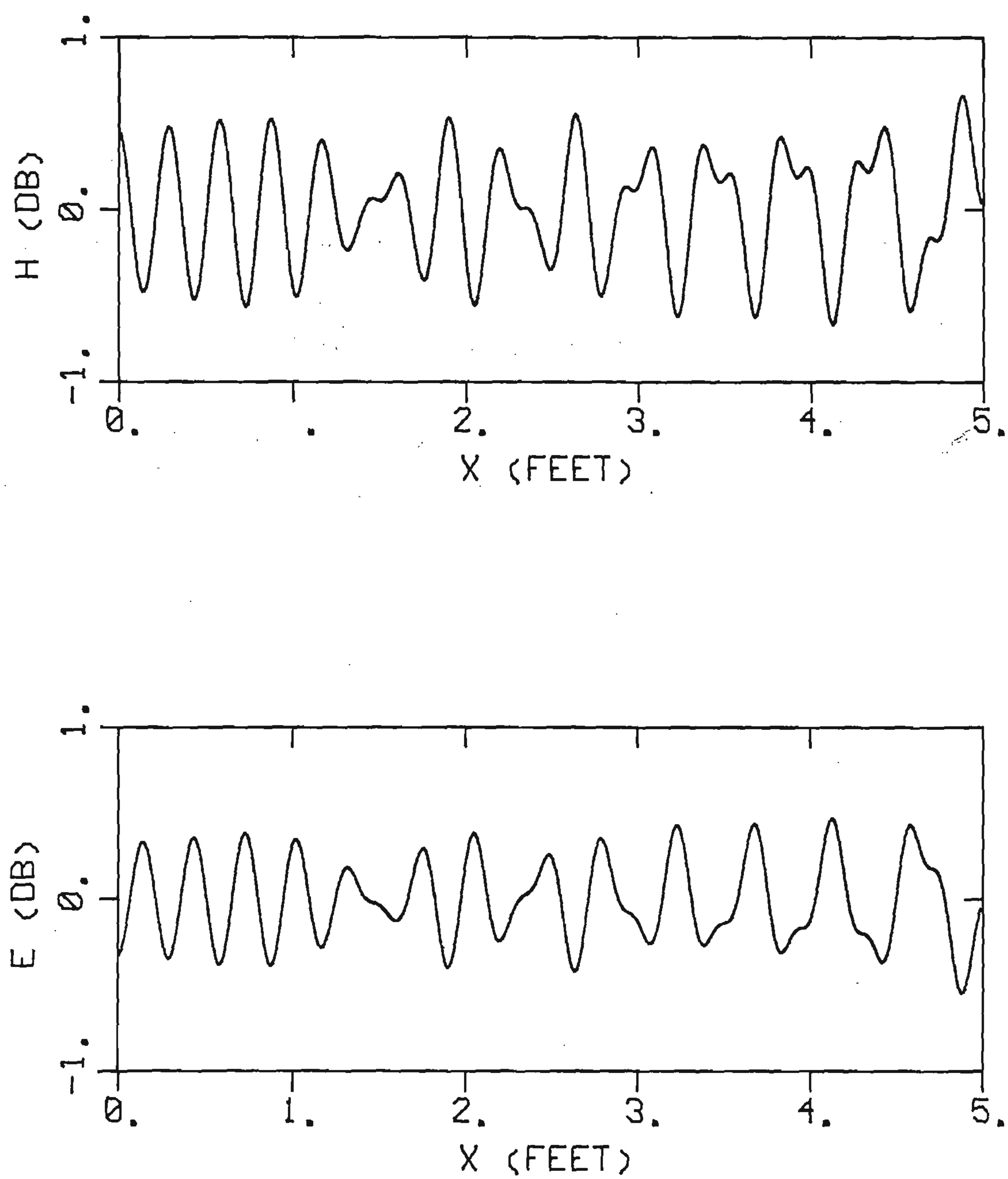


Figure 7. Computed fields in the target zone 28 feet from the apex of a parabolic cylinder reflector 20 feet wide. Assumed frequency is 10 GHz.

while for H-polarization,

$$X_1 + Y_1 = X_2 + Y_2 = 3.43 \tag{21}$$

and

$$(2!kR_1)^{1/2} = (2!kR_2)^{1/2} = 109.2 \tag{22}$$

Thus, the magnitude of the diffracted field is 0.44 for E-polarization and 0.064 for H-polarization, and the total excursion in the net field strength (from minimum to maximum values) will be

$$20 \log \frac{1 + 0.044}{1 - 0.044} = 0.77 \text{ dB (E-polarization)} \tag{23}$$

$$20 \log \frac{1 + 0.064}{1 - 0.064} = 1.09 \text{ dB (H-polarization)} \tag{24}$$

These values can be read approximately from the plots of Figure 7. The same kinds of calculations can be performed at the end of the scan near x = 5 feet.

These are worst case figures corresponding to the circular rim of a paraboloidal reflector in the three-dimensional case. Some attempts have been made by commercial producers to minimize edge diffraction by the use of edge serrations, and apparently that approach is successful. One version of an offset paraboloid is sketched in Figure 8. The sketch shows the paraboloid contour as it might appear to an observer stationed well away from the reflector on the focal axis. The reflector is approximately 12 feet wide and 12 feet tall; the design criterion for the edge contour is not known, but as judged from experimental field scans across the target region, the serrated design reduces edge-diffracted fields [5]. The approximate cost of this commercial reflector was $120,000 in 1978 and $160,000 in 1981.

Horizontal and vertical scans through the target region, as presented by Bodnar, _et al._,[5] do not exhibit the highly periodic oscillations seen in

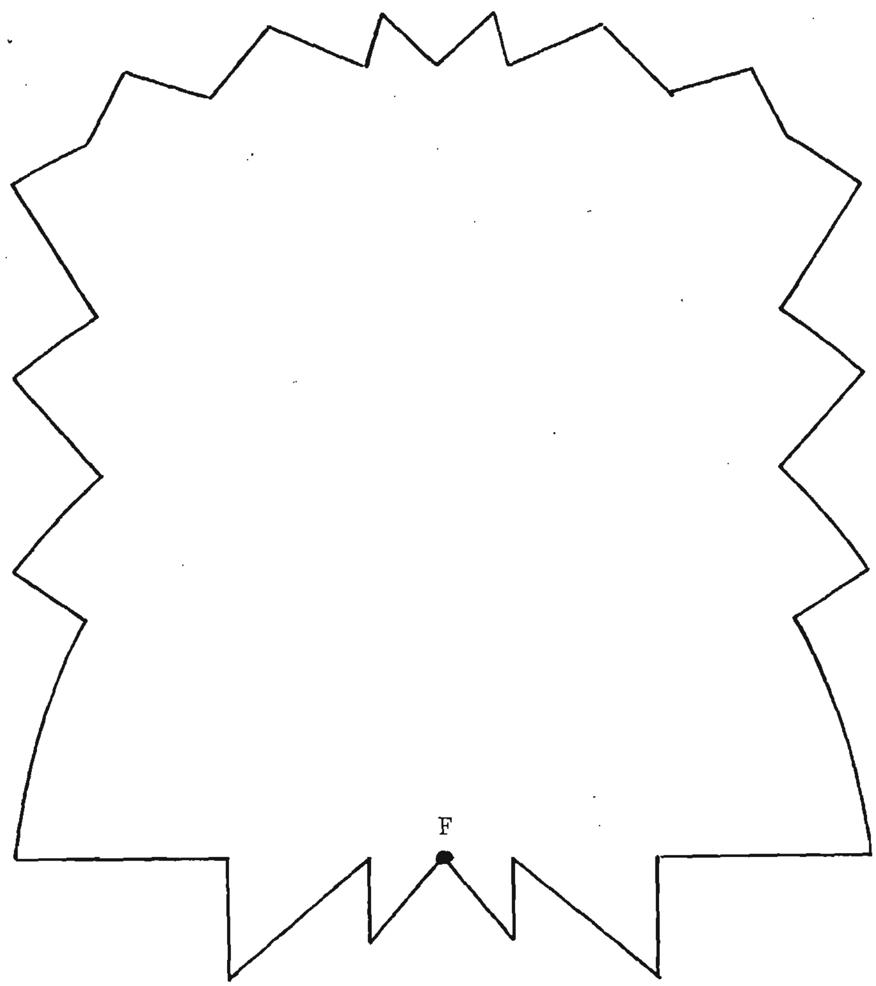


Figure 8. Approximate shape of Scientific-Atlanta's commercial 12-foot reflector.

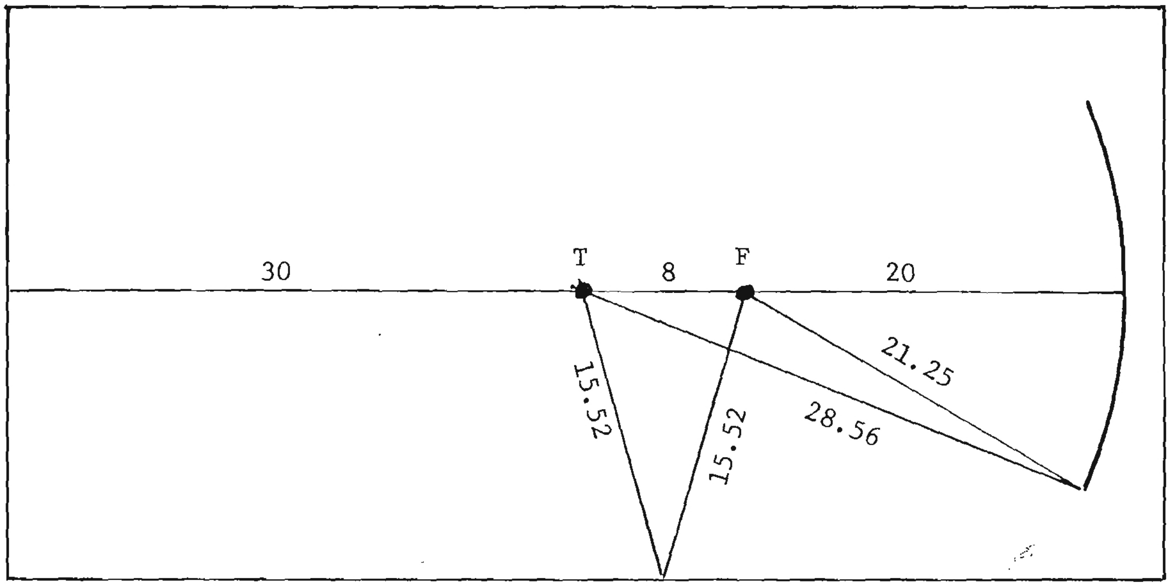
Figure 7. Vertical field scans show some erratic, but small, perturbations in the field structure, and the field strength tapers by about 1 dB over a total distance of 5 feet. Horizontal field scans are somewhat more regular and cover about 6 feet. If a 1.5 dB taper can be tolerated, the width of the useful horizontal dimension is approximately 8 feet. One suspects, however, that it take some "fine tuning" of the feed position, feed pattern, and the absorbent material lining the anechoic chamber to achieve such uniformity in the target test region.

The amplitude taper is due in large measure to the radiation pattern of the reflector feed. The pattern must be broad, and ideally it should have a slight dip in the direction of the apex of the paraboloidal reflector as mentioned earlier. This is because the distance from the feed to a point on the reflector surface varies, hence the incident power level decreases away from the apex unless compensated for by careful design of the feed antenna.

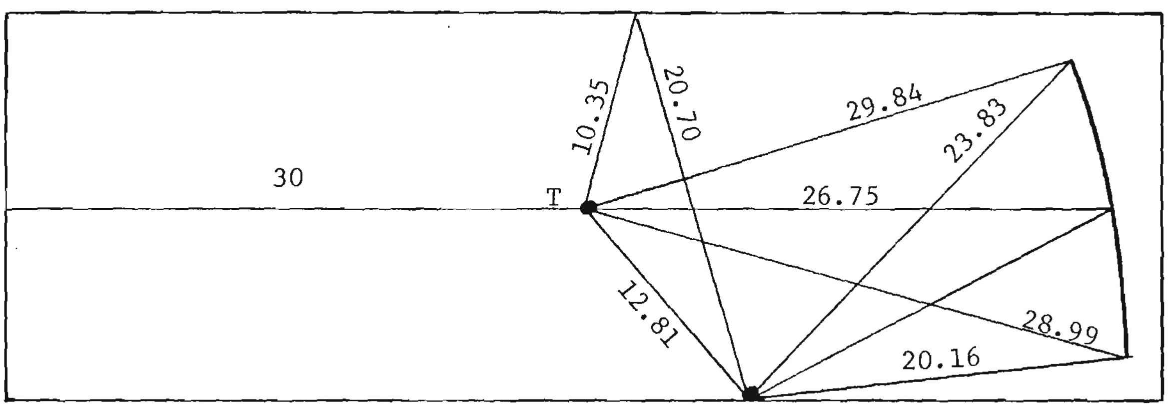
Whether the pattern dip is provided or not, the edges of the reflector are strongly illuminated. In addition, the presence of the anechoic chamber walls provide ample opportunity for target-chamber interactions and target-chamber-reflector multipath conditions. Some of the distances involved in these interactions are sketched in Figure 9. For the purpose of calculating the various path lengths, the chamber was assumed to be 30 feet wide, 60 feet long, and 20 feet high (internal dimesnions), with the reflector surface positioned 4 feet from the end wall.

Figure 10 is a survey of the round-trip distances associated with the various interactions in the chamber of Figure 9, and Table 1 is a list of the major interactions. Not all possible interactions are listed. There are three collections of signal returns that may contaminate the measurement of the target return occurring at a round-trip distance of 96 feet.

The first group is the direct return from the edges of the reflector. Since each section of the edge lies a different distance from the feed, these returns will consititute a continuum of return signals. The last of them arrives at the feed about 32 nanoseconds (corresponding to about 32 feet) before the arrival of the target return. If these returns are large enough to require receiver protection, the receiver must recover its full sensitivity in



Plan View



Elevation View

Figure 9. Some of the multipath distances for target-chamber-reflector interactions.

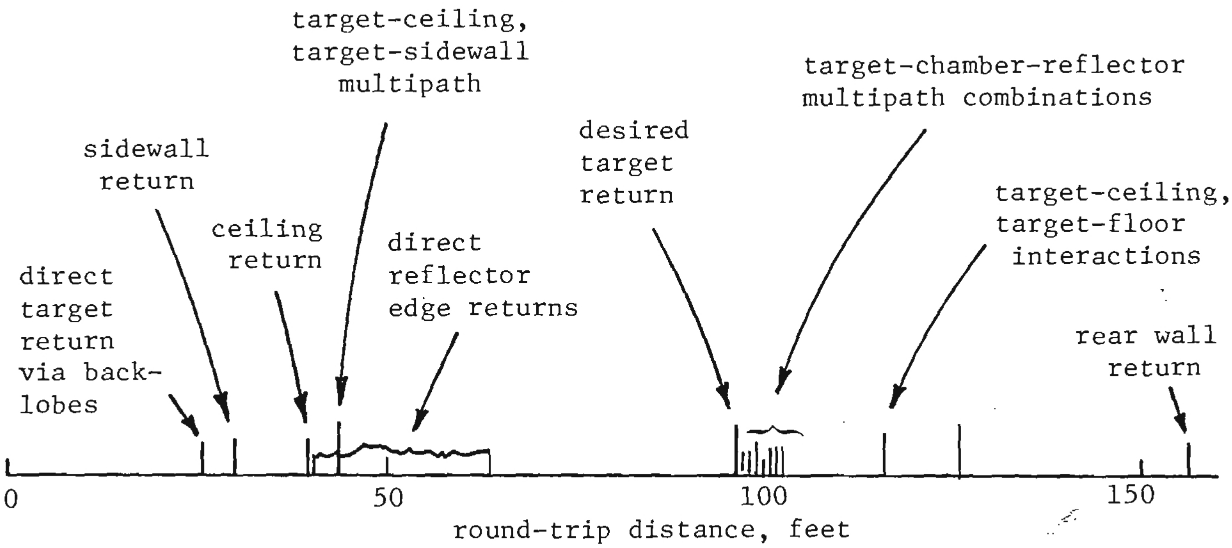


Figure 10. Compact range signal history

Table 1.

Round-trip distances

signal source	distance, feet
direct target return (via feed backlobes)	25.6
sidewall return	30.0
ceiling return	40.0
reflector edge returns	40.3 to 63.9
ceiling-target multipath	43.9
sidewall-target multipath	43.9
target return	96.0
target-lower reflector edge multipath	97.2
target-upper reflector edge multipath	100.1
target-side reflector edge multipath	101.7
target-floor-lower reflector edge multipath	98.0
target-ceiling-upper reflector edge multipath	99.0
target-wall-side reflector edge multipath	102.7
target-ceiling interaction	116.0
rear wall return	156.0

barely 30 nanoseconds, which complicates the receiver design. No attempt has been made to estimate the level of the edge reflections, hence we cannot state with certainty how long the receiver must be protected after the main bang and what the receiver recovery time must be. Those estimates should be made.

The second group of returns is clustered very close to the target return itself. They include interactions between the target and the edges of the reflector, with and without an intermediate bounce off the chamber walls. They all arrive within a time corresponding to a span of about 5 feet, and the first one arrives barely a nanosecond after the target return. It will be very difficult to adequately separate the nearest of these returns from the desired target return. Since the interactions all involve the reflector edges, it might be necessary to devise edge treatments to suppress the effect. Edge diffraction can be controlled [6], but the treatment, if a treatment is required, will require a detailed numerical study. No attempt has been made to estimate the magnitude of the interactions. Such an estimate would have to include consideration of the bistatic patterns of two or three simple targets such as a sphere, a flat plate, and a circular cylinder. These estimates should be made.

The third group of returns involves the interactions between the target and the chamber walls, but with no intermediate interaction with the edge of the reflector. These contributions can be suppressed by using high quality absorbing material on the walls in the vicinity of the target zone. This group of returns could also be displaced farther in time from the target return by increasing the width and height of the anechoic chamber.

In its previous report [1], Georgia Tech estimated the cost of a 20 by 40 foot reflector to be about $2.1 million, which included engineering and design, fabrication, installation, profile alignment, and other details of construction. Assuming all costs would remain the same for a smaller reflector, except for fabrication, and that fabrication costs could be reduced by 50%, a smaller (15 by 20 foot) reflector would cost about $1.2 million. But this figure may be too low; Scientific-Atlanta, the only producer of commerical compact ranges, is allegedly considering marketing a compact range for 15-foot targets that would cost about $5 million to develop.

In view of the cost difference between the existing compact range and larger versions (several million dollars) and the nearly acceptable performance of the existing compact range for 8-foot targets, Georgia Tech feels that slightly degraded accuracy would be an acceptable trade-off for a great reduction in the cost of acquiring a compact range. However, the final decision should also account for anticipated RCS measurement requirements in the future.

SECTION 3
LENSES

In Georgia Tech's previous report in this study, the size of the target and the shortness of the range to the target resulted in a short focal length. This in turn required a thick lens which, for a target size of 20 feet, would have weighed in excess of 40 tons. Aside from the uncertainties whether a lens that size could even be fabricated, the weight is prohibitively high.

But for a smaller target measured at a greater distance, a considerable reduction in size can be achieved. For the sake of estimating the weight and thickness of such a lens, let us assume that a clear, 100-foot long propagation path can be established. Ignoring for the moment where the anechoic chamber might be placed and what its configuration might be, we still require at least 25 feet between the lens and the target in order to give adequate time spacing (50 nanoseconds) between the lens return and the target return.

Assuming a 10-foot target must be accommodated and that the lens diameter should be twice that, we have a diameter of 20 feet and a focal length of 75 feet, for a F/D ratio of 3.75. From Figure 3 of Reference 7, for an index of refaction of 1.63, corresponding to a polymethacrylate material (Lucite or Plexiglass), the lens thickness is 0.0525 times its diameter. For a 20-foot lens, this is 1.05 feet. From Figure 4 of the same reference, the normalized volume (with respect to the cube of the diameter) is 0.0204, hence the volume is 163 cubic feet, and with a density of 74.26 pounds per cubic feet, the lens would weigh 6.1 tons. This is still heavy, but not out of the question.

Nevertheless, the lens is still a very large one and the technical difficulties of building a large lens probably put it beyond the state of the art. Some of these difficulties were described in the previous report [Reference 1, pp. 14-16]. Furthermore, the facility would have to be at least 130 feet long and 30 feet wide, and there is no convenient way to erect the facility alongside the existing structure. Thus, Georgia Tech iterates its previous recommendation that the lens concept of achieving far-field conditions in a compact range be discarded.

SECTION 4
SUMMARY AND RECOMMENDATIONS

In this study, Georgia Tech investigated three ways to achieve far-field conditions in a foreshortened distance. These were an offset paraboloidal reflector, a solid dielectric lens, and a phased array antenna. The phased array was eliminated as being too costly and too complicated. The lens was eliminated as being beyond the state of the art. The paraboloidal reflector is the recommended approach because reflector technology is within the state of the art. The anechoic chamber housing the compact range can be erected adjacent to the existing facility and there is even room enough for a model preparation area, as shown in Figure 2.

It may cost as much as $5 million for the design, development, and fabrication of a reflector large enough for a 25-foot target, and perhaps $2 million for a 10-foot target. If degraded accuracy is allowed, a commercial compact range reflector can be acquired for under $200,000. However, the target test region for such a reflector would always be limited in size.

Diffraction from the reflector edges will introduce multipath interference signals that are received within 1 to 6 nanoseconds after the desired target return; the earliest interference signal will be difficult to separate from the target signal. Direct returns from the reflector edges will precede the target return by only 30 nanoseconds or so. Depending on the relative strengths of these echos, it may be necessary to protect the receiver, thereby imposing fast receiver recovery specifications.

The magnitudes of these potential sources of interference have not been estimated, and those estimates need to be made before the receiver design parameters are established. Therefore an analytical study should be performed to assess the impact of the signals. If that study shows the levels are too high, methods of reducing the edge contributions should be explored. In addition, interactions between the target and the chamber walls can be reduced by using high quality absorbing materials in sensitive areas of the chamber.

In summary, Georgia Tech concludes the following:

1. The offset paraboloidal reflector should be pursued as the method of implementing a compact range.
2. The size of the reflector can be chosen only by management because of the trade-off in cost versus target size.
3. Multipath interactions between target, chamber, and reflector will influence the design of the radar instrumentation.

Our recommendations are:

1. Perform a study to estimate the magnitudes of the interfering signals.
2. If the interference is too high, study the feasibility of treating the edges of the reflector.
3. Assess the influence of the interfering signals on the instrumentation design.

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